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Methods for Visualizing the Explosive Remnants of War

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1 Abstract

This study aimed to answer the question how GIS can help decision makers visualize the problem of contamination by explosive remnants of war (ERW). We thus explored a set of six cartographic visualization methods and systematically evaluated their usefulness with respect to four categories of stakeholders in the humanitarian demining process (i.e., database administrators, operations officers, directors of national mine action authorities, and donors) at four geographical scales, ranging from municipal to global. The main application of our work is for stakeholders involved in humanitarian demining. We provide them with a comprehensive framework for visualizing ERW hazards at the geographical scale at which they have to make decisions, as well as customized cartographic visualization tools and recommendations to help them make informed decisions. For example, we provide potential donors with a method for obtaining a global overview of ERW contamination while remaining aware of regional variation and hot spots. We also enhance cartographic visualization capabilities using traditional kernel density estimation by customizing key parameters. Specifically, we propose a method for adjusting kernel bandwidth for datasets with highly heterogeneous spatial distributions and a method for generating kernel surfaces from polygon data that consists of infilling the polygons with points before using them as inputs in the kernel density estimation.

Keywords : Humanitarian Mine Action; Explosive Remnants of War (ERW); Cartographic Visualisation; Kernel Density Estimation; Data Sharing

2 Introduction

The term Explosive Remnants of War (ERW) has its origins in international humanitarian law[1]. ERW includes all explosive contamination from war, such as landmines, unexploded ordnance (UXO), improvised explosive devices, and abandoned munitions storage. According to the United Nations Mine Action Service (UNMAS), ERW affect over 70 countries, and thousands of casualties are recorded each year (UNMAS 2011). In Afghanistan, in 2000 and 2001, 81% of those injured by ERW were civilians, and 46% were 16 years old or younger (Bilukha *et al.* 2003). The effects of ERW are not limited to the individuals who are directly impacted. They represent a significant challenge for society in affected countries. Situated at the crossroads of humanitarian and development activities, mine action aims both to reduce the impacts of the presence of ERW on local populations and to return cleared land to local communities for land rehabilitation.

This paper aims to answer the question of how visualization of ERW contamination can support mine action decision-makers at the policy level, e.g., in determining national and international mine action priorities, assessing humanitarian impact, or estimating the financial costs of reducing ERW impacts. Building on the work of Lacroix *et al.* (2002) and Delhay *et al.* (2005), who suggested that maps improve the planning of demining campaigns, this paper investigates how maps can be used to help decision makers visualize the problem of contamination by ERW. This paper makes several methodological contributions intended for the abovementioned end users. We conducted an analysis of the user requirements for visualizing ERW contamination. We proposed six different cartographic visualization methods that can be used to display contamination by ERW hazards. For cartographic visualization using kernel density estimation (KDE), we proposed two extensions of the existing method: first, a simple yet effective technique of adjusting kernel bandwidth for datasets with highly heterogeneous spatial distributions; and second, a method for generating a KDE from polygon data by infilling polygons with data points before using them as inputs to the KDE. Finally, our comparative

[1] Protocol V to the Convention on Certain Conventional Weapons, , adopted in November 2003 by the Meeting of the State Parties to the Convention, defines explosive remnants of war (ERW) as unexploded ordnance (UXO) and abandoned explosive ordnance. UXO (also known as “duds”) “refers to munitions (bombs, shells, mortars, grenades and the like) that have been used but which have failed to detonate as intended, usually on impact with the ground or other hard surface” (GICHD, 2010, p. 13)

evaluation of the strengths and weaknesses of the six proposed methods provides overall recommendations for the use of each cartographic visualization technique by the four different categories of mine action stakeholders at four different scales.

In this study, we examined cartographic visualization methods using existing contamination data managed by a set of national authorities with the Information Management System for Mine Action (IMSMA), which was developed by the Geneva International Centre for Humanitarian Demining (GICHD). The GICHD is a non-profit foundation established by Switzerland and several other countries in April 1998. It strives to eliminate ERW and to reduce its humanitarian impact. The GICHD develops standards, provides capacity-development support, and conducts research activities. The actual implementation of mine action activities is not within its scope of work. Instead, the mission of the organization is to promote tools and methods that improve the performance of mine action actors such as international organizations and the governments of affected countries. In this role, the GICHD often represents the mine action community in interactions with researchers and the academic community. In our project, the involvement of the GICHD was central to establishing contact with the community of users that would apply the methods developed in the study and in building an understanding of the needs of that community.

The emphasis of this paper is on identifying and developing methods for displaying and conveying ERW contamination data using the existing data from IMSMA installations in a set of selected countries. Consequently, methods for detecting contamination or collecting data on potential unknown contamination, such as remote sensing, are excluded from the paper. Such methods are well addressed in the work of other authors, e.g., Zare *et al.* (2008) and Witmer and O'Loughlin (2009).

The paper is organized as follows. We begin in Section 3 by orienting the reader to the terminology and standard processes used in mine action work and by determining the requirements of contamination visualization for the four identified stakeholder groups, followed by a brief description of the experimental setup in Section 4, including the selected case study countries and their respective datasets. In Section 5, we review existing research related to the visualization of ERW contamination data. This is followed in Section 6 by the introduction of the six selected cartographic visualization methods that were tested according to the requirements set out in 3. Sections 7 and 8 elaborate on the technical elements of the cartographic visualization methods that use KDE. Section 9 provides a comparative discussion of the proposed cartographic visualization methods with respect to the criteria identified in 3.

Finally, the paper ends with our conclusions and a discussion of the use of the proposed cartographic visualization methods by mine action stakeholders.

3 Background

3.1 User Focus Group

A user focus group was set up with the support of the GICHD. The focus group consisted of two dozen individuals, including mine action experts, GIS experts or both. The results of a self-assessment of the participants' individual areas of expertise demonstrated that the focus group broadly represented the entire user community[2]. The participants, who represented eight different organizations, had intervened directly or through partnerships in more than 60 mine-affected countries. The input from these experts was supplemented by input from GICHD staff, who are in frequent contact with decision makers as part of their work and are responsible for the development of the GIS component of the IMSMA, which is the most widely used GIS tool in the field (Eriksson 2011). With this in mind, we considered the panel of experts to be representative of the mine action community and an appropriate sample for our research.

Two main meetings were held with the user focus group: one was held in April 2011 and the other in February 2012. The first meeting led to the formulation of requirements for ERW visualization. Following the second meeting, the end user experts were also asked to evaluate the results of our research, as discussed in Section 9.

3.2 Mine Action Stakeholders

Based on our review of the mine action literature and the discussions in the first user focus group meeting, four groups of actors were identified.

Users outside the core mine action field include donors (public and private organizations and individuals) and the general public, which is considered a potential donor. These actors need a global overview of mine action to decide which country to fund. In 2009, 83% of funding for mine action came from international sources (Devlin and Naidoo 2010). Donors no longer consider mine action to be an immediate humanitarian response; rather, it is considered to be part of a broader process that includes conflict prevention, protection, mitigating socio-

[2] Information management: 11 experts; strategic management: 1 expert; national program management: 4 experts ; operational planning: 3 experts; database management: 6 experts; and GIS: 8 experts

economic impacts, reintegration (Devlin 2010), humanitarian assistance, and care for survivors (Devlin and Naidoo 2010).

Directors of national mine action authorities are responsible for ensuring that mine action activities in their respective countries are implemented in compliance with international law, standards, and policies (GICHD 2007, GICHD and UNMAS 2011). These authorities work in collaboration with other national and international bodies, governments, communities, private companies, and initiatives. They regularly produce summaries of their goals and achievements for distribution to donors and the broader mine action community (UNDP 2011).

The *operations officers* in a mine action authority are part of a small- to large-scale prioritization process. They first must refer to contamination maps at the regional or sub-regional scales to decide where to conduct mine action activities. In a second step, large-scale one-to-one dot maps (also called point symbol maps; cf. Section 6.1) combined with other elements (e.g., topography, key agricultural land, and infrastructure, as described by Gasser *et al.* (2011)) are used to decide how to access mined areas. Operations officers are experts in mine action and explosive ordnance disposal and do not necessarily have GIS expertise or experience.

Similarly, *database administrators* do not necessarily have high competency in GIS. Part of their work consists of probing the database for inaccuracy or incompleteness. Spatial data attributes such as coordinates, area type, and area are commonly checked at large scales (1:50'000 to 5'000) in coordinated efforts between database administrators and operations.

3.3 Mine Action Data

Mine action data are collected in the field and recorded in the IMSMA relational database management system. IMSMA is an ArcGIS Engine-enabled, self-contained information system that was specifically developed for mine action centers in mine-affected countries (Eriksson 2011). As of 2012, more than 60 centers are using this software for information management. Each country using the system owns their data. IMSMA^{NG} is therefore not a global repository of mine action data. National databases are accessible to the GICHD on request for technical support purposes, but national authorities decide whether to share their data with other mine action stakeholders. Most stakeholders struggle to get insight into the contamination data. In particular, donors do not have the access they need to complete, global-scale information about contamination problems.

Because each mine-affected country is responsible for collecting data within its territory, the IMSMA allows for customized methods of data collection and entry. The freedom of IMSMA users to choose the data that are collected and the data formats results in very heterogeneous data across the different countries. Nevertheless, this design choice was made to make the system adaptable to the diverse types of information management required in the field of mine action.

Furthermore, the capacity of each country to control the quality of the incoming data varies, resulting in a large spread in data quality. The reliability or confidence level of a given record is most commonly indicated by a designated 'hazard type,' which the user assigns to the data either when collecting the data in the field or when entering it into the database. The hazard types defined by UNMAS (2003) are suspected hazardous area (SHA), confirmed hazardous area (CHA), and defined hazardous area (DHA). The definitions of these types are under constant review; for the purpose of this study, we used the UNMAS 2003 definition.

A SHA is an area suspected of containing a hazard. An SHA is often identified when a local population reports that a hazard is present, and SHAs typically do not have a known perimeter. Instead, an SHA is represented by point indicating the approximate location or, more rarely, a circle. A CHA is an area identified in a non-technical survey for which the need has been confirmed for further intervention, either through a technical survey or clearance activities.

A CHA is typically represented by a polygon; compared to an SHA, a lot more information is available about the area. For instance, information about the suspected type of contamination, potential economic use of the area after clearance, topography, and vegetation is often included.

A DHA refers to an area within a CHA that requires full clearance. A DHA is normally identified using original and reliable minefield records.

In a typical demining process, the status of a hazardous area evolves from SHA to CHA and then to DHA. The reliability of hazardous areas is considered high for DHA, medium for CHA and low for SHA.

In IMSMA^{NG}, spatial data are stored as 2-D coordinate pairs that represent polygon vertices, polyline vertices, or points, with an additional attribute recording an estimated or calculated area. In general, the more that is known about a hazard, the more likely it is that the hazard has been recorded as a polygon (Figure 1). Therefore, SHA are most commonly stored as a single point approximation, sometimes with an estimated area as an attribute. The exact extent of the hazardous area remains unknown until after the hazard has been cleared. Most countries' databases contain many more SHA than DHA records.

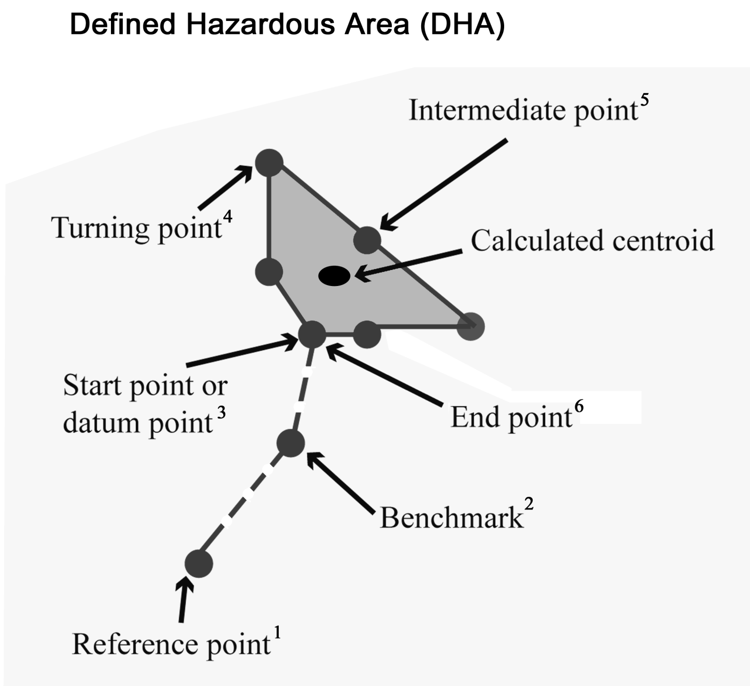


Figure 1: A DHA stored as a polygon in the IMSMA^{NG} MySQL database

[1]Landmark or reference point: a fixed point of reference located some distance outside the DHA. Landmarks should be easily recognizable features, such as a road junctions or bridges, that can be used to navigate to one or more benchmarks

[2]Benchmark: a fixed point of reference used to locate a marked area or DHA. Benchmarks are typically located at a short distance outside the DHA

[3]Start point: the first point of a polygon

[4]Turning point: a fixed point on the ground that indicates a change in direction along the perimeter of a DHA

[5]Intermediate point: a point used between turning points that are more than 50 meters apart

[6]End point: last turning point (typically, same coordinates as start point)

In summary, the degree of completeness of a database and the hazard confidence levels vary significantly among countries. Most contamination data are sensitive. The exact location of mines cannot be revealed to a large audience because civilians or criminals could use this information to steal mines for illicit re-use or to sell on the black market as explosives.

3.4 Requirements of Visualising ERW Hazards

The results of the first user focus group meeting are summarized below. The numerous requirements for the visualization of ERW hazards were sometimes contradictory and overlapping. Although the participants' responses identified a wide spectrum of user needs, groups of users tended to focus their responses at a particular scale (which ranged from global to local) and to agree on their requirements.

- Maps should be precise and provide an accurate representation of the nature of the contamination.
- At the same time, data confidentiality must be preserved. In terms of data representation, a compromise must be found between data obfuscation and the previous requirement for maps.
- Users must be able to control and adjust the representation of the contamination data. For example, users operating at a global scale have different needs from those operating on the national or local level. The objective of using kernel density mapping and the balance between precise maps and data obfuscation vary across the different scales of use. These aspects of data visualization also vary among countries, which makes it impossible to use a standardized solution for each scale. Consequently, the methods must be developed that are flexible enough to let the users select the degree of obfuscation and level of detail that best addresses their needs,
- Most mine action stakeholders are not GIS experts. The messages conveyed by the maps should therefore be intuitive to avoid misunderstandings.
- It should be possible to combine contamination maps with other types of information (e.g., socio-economic data) to visualize relationships between contamination and other decision-making factors.
- The sovereignty of countries should be respected. The method chosen by one country to visualize contamination should not affect the data representation used by neighboring countries.
- Adding to the complexity, some country borders are disputed and, in the interest of maintaining neutrality, cannot be shown on maps. Because landmines are more commonly located in these contested areas, the cartographic visualization process must be performed carefully. This reinforces the need for users to be able to control the representation of contamination data on a case-by-case basis.

Though secondary to the above requirements from users, it also became evident that the nature of the mine action data and the IMSMA system posed a set of technical challenges. These challenges included the large volume of data; data storage in non-spatial repositories; and a high degree of heterogeneity in the quality, spatial accuracy, reliability, degree of completeness, and spatial distribution of the ERW data.

4 Experimental Setup

Our test data included data subsets from six databases: Afghanistan, Cyprus, Iraq, Lebanon, South-Central Somalia, and Tajikistan. Because our intention was for the cartographic visualization methods analyzed in this paper to be used in any country affected by ERW, the countries were selected to be representative prototype countries based on their diversity in terms of environmental, historical, and cultural characteristics, as well as their predominant demining techniques. All of the selected countries currently use the IMSMA.

The sample sizes (Table 1) ranged from less than 100 records for Cyprus to several thousand records for Afghanistan and included either points (and polygon centroids) or polygons. Spatial statistics revealed substantial differences in the geographical distributions of the ERW in the selected countries. In some countries, the data were more randomly dispersed in space (Herzog 2010), while the data clustering was more pronounced in other countries. For example, approximately 90% of the hazards in Cyprus are located in the vicinity of the sparsely populated buffer zone that has divided the Republic of Cyprus into two parts since 1974, following a conflict between the Turkish and Greek Cypriots. In contrast, more than 30% of the Afghan ERW was found in areas where the population density is higher than 100 inhabitants/km^2, and 47% was no further than 1 km from a road.

The use of heterogeneous data from prototypical countries enables a robust representation of worldwide contamination datasets.

Table 1: Overview of the test datasets

Test country	**Number of points**[1]	**Number of polygons**[2]
Afghanistan	6’644	6’443
Cyprus	94	89
Iraq	196	195
Lebanon	1’496	1’496
South Central Somalia	133	3
Tajikistan	202	1

[1] Points and polygon centroids

5 Visualising Hazards and Mine Hazards: State of the Art

According to Lorz *et al.* (2010) and others, hazard mapping has become of significant interest for its applications in financial and environmental risk management. The mapping of hazards and disasters (e.g., floods, fires, earthquakes, cyclones, and volcanic eruptions) is widespread, especially in the form of maps or web map services (WMS) on interactive global data platforms (ESA 2011, GEO 2011, Giuliani and Peduzzi 2011, and many others).

Some attempts have been made to apply remote sensing and GIS analysis in the field of mine action, mainly focusing on sensors that detect individual ERW through the use of satellite data (Witmer and O'Loughlin 2009), hyperspectral imaging (Zare *et al.* 2008, Wong, 2009) or ground-penetrating radar (Havens *et al.* 2009). Benini (2000) and Benini *et al.* (2003) coupled landmine data with socio-economic data at the national level to determine clearance priorities, and Riese *et al.* (2006) described a GIS-based approach to making probabilistic forecasts about the presence of ERW to support decision-making about the allocation of demining resources. In another probabilistic approach, Vistisen (2006) employed Bayesian inference to develop a risk model that quantified the extent to which a given minefield poses a risk to a society. Williams and Dunn (2003) presented an example of the use of GIS in a participatory process during an impact assessment of landmines in selected villages in Cambodia. Andersson and Mitchell (2006) used inverse-distance weighted interpolation to generate population-weighted raster maps for use in the evaluation of mine risk education. More recently, Alegría *et al.* (2011) used a variety of geostatistical techniques and kernel density estimation (KDE) to analyze and map landmine risk. While the study by Alegría *et al.* is the most similar to our study, it differs from our work in several important respects. The previous study was restricted to a single scale, rather than using a range of scales from local to global; the ERW data were point data, with no polygon data; and the study was essentially a preliminary study to explore the utility of various analytical tools offered by a particular software package (CrimeStat; Levine 2010) for visualizing ERW risk. Nevertheless, the previous study does clearly highlight the potential for using density-based methods for visualizing ERW, and the methods described are similar to some of the methods introduced below. Maps based on KDE (also called heat maps; Trame and Keßler 2011) are widely used to analyze and visualize spatial distributions of discrete presence or counts data given at point locations. In animal ecology, they are today the preferred methods for estimating and delineating the home range of animals, superior to convex hulls (Katajisto and Moilanen 2006, Wartmann *et al.* 2010). A selection of recent applications of KDE in geography include delineation of vernacular place names from web documents (Jones *et al.* 2008), mapping of concentrations of surnames in Britain (Cheshire and Longley 2012), delineation of city centres from topographic map data (Lüscher and Weibel 2013), mapping of

environmental risks (Lewis and Bennett 2013), as well as mapping and visualizing social values associated with places (Brown and Weber, 2012, Sherrouse *et al.* 2011, Van Riper *et al.* 2012).
With regards to the use of cartographic visualization in the field of mine action, only a few maps showing ERW contamination have been published on the web to date (e.g., ICBL 2011b, ITF 2001, Lokey 2001, Rekacewicz 2003). Most of them are difficult to read, are not interactive, and are most likely not up-to-date, based on their dates of publication. ICBL (2011b) provides one worldwide choropleth map that shows four degrees of mine contamination at the country level: very heavy, heavy, low, and none. Two websites (Sasi and Newman 2006, Hennig 2011) show cartograms displaying landmine casualties at the global level, but they do not show contamination by ERW. UNMAS provides monthly updated information about UXO removal and mine risk education in Libya using an interactive web platform (UNMAS 2012).
While ERW visualization projects are rare on the web, printed one-to-one dot maps are extensively used by operations and database analysts at the field work level. Choropleth maps are currently in use in several national mine action programs. In particular, the Colombian Programa de Acción Integral Contra las Minas Antipersonal (PAICMA 2012) has published a choropleth showing the number of victims per administrative unit.

6 Evaluated Visualisation Methods

There are multiple ways to represent a spatial phenomenon graphically. For ERW contamination, the difficulty is finding the appropriate cartographic visualization method because the requirements for visualizing ERW data are numerous. Cartographic textbooks such as Slocum *et al.* (2009) suggest a wide spectrum of cartographic methods, including point symbolization, choropleth maps and interpolation. Müller *et al.* (2006) recommend that hazard maps use continua, quantitative and absolute data, and smooth statistical surfaces.
Six methods (A, B, C, D, E and F) were examined in this study. They are described in this section and illustrated in Figure 2.

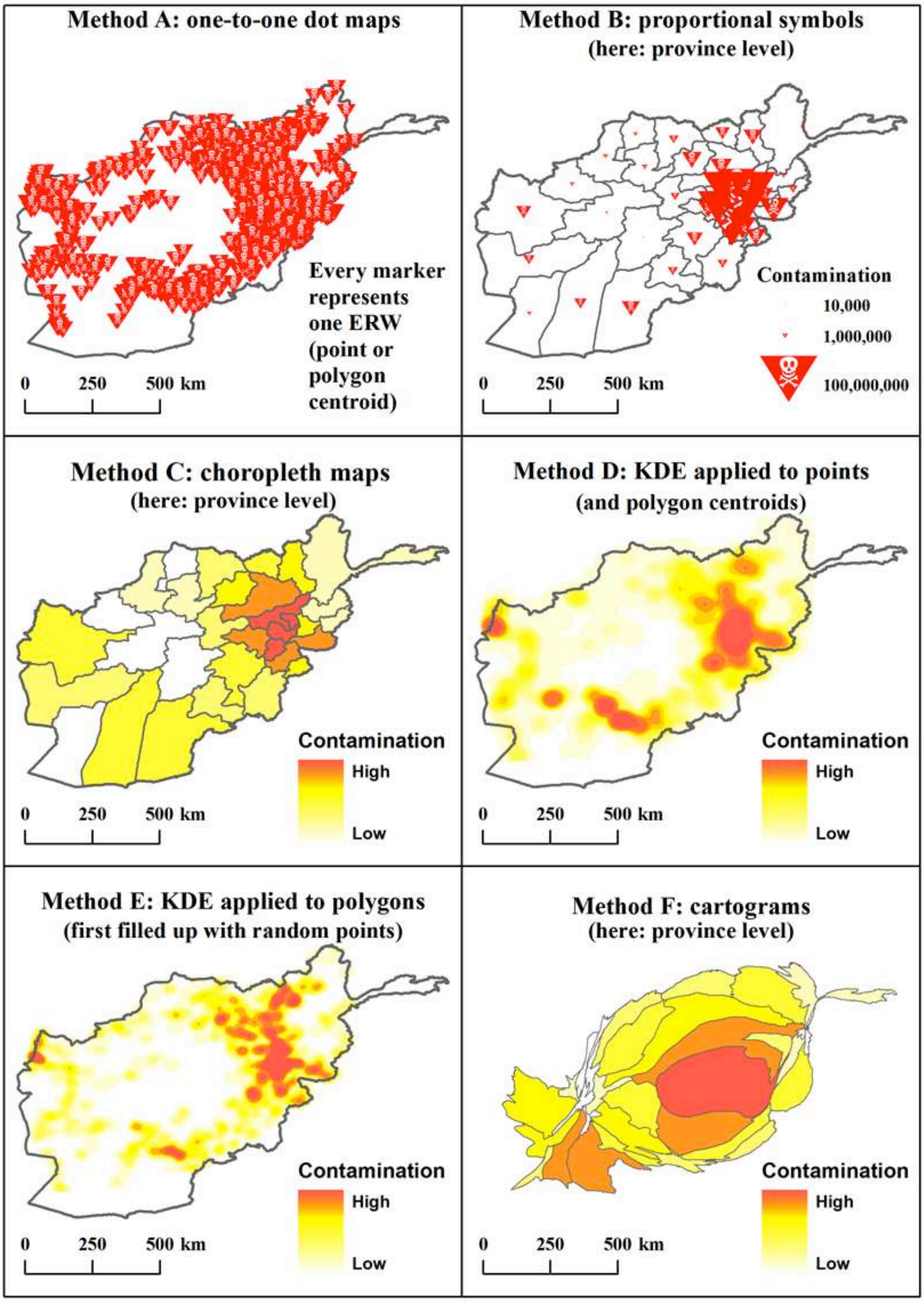

Method A: one-to-one dot maps
Every marker represents one ERW (point or polygon centroid)
0 250 500 km
Method B: proportional symbols
(here: province level)
Contamination
10,000
1,000,000
100,000,000
0 250 500 km
Method C: choropleth maps
(here: province level)
Contamination
High
Low
0 250 500 km
Method D: KDE applied to points
(and polygon centroids)
Contamination
High
Low
0 250 500 km
Method E: KDE applied to polygons
(first filled up with random points)
Contamination
High
Low
0 250 500 km
Method F: cartograms
(here: province level)
Contamination
High
Low
0 250 500 km

Figure 2: Contamination by ERW: overview of the six tested methods (Afghanistan, 6’644 ERW)

Our study should not be considered a comparative study of cartographic visualization methods because the methods in question are not meant to serve the same cartographic purpose. Rather, we aimed to identify the best methods for addressing the requirements of each separate user group.

6.1 Method A: One-to-one dot maps

In one-to-one dot maps (O’Sullivan and Unwin 2010), also called point symbol maps (Slocum *et al.* 2009), each ERW is represented by a point symbol marker. As an example, the coordinates for the 6’644 ERW areas in Afghanistan, which were originally stored in the IMSMA^{NG} repository, are directly displayed in Figure 2. Every marker represents a single point or polygon centroid. This method is based on one-to-one mapping and is an example of pure geovisualization (O’Sullivan and Unwin 2010, p.65) (i.e., there are as many symbols as represented features).

6.2 Method B: Proportional symbols

In this method, a contamination value is estimated for each administrative unit by summing the estimated or calculated areas of the ERW located within the unit. Each administrative unit is represented by a symbol whose size corresponds to the level of contamination, with larger symbols indicating a higher level of contamination. Method B is useful for representing absolute count data, such as the number of ERW or the overall contaminated surface in an administrative unit.

6.3 Method C: Choropleth maps

A choropleth map is a thematic map that shows a generalized depiction of quantitative area distributions (Peterson 1979). In method C, ERW areas are aggregated by administrative unit and colored according to the contamination level, which is normalized by the area of the units. Choropleth mapping is currently the most widely used method for generating maps (O’Sullivan and Unwin 2010).

6.4 Method D: KDE applied to points and polygon centroids

K DE has been used in many fields, including crime mapping (Chainey and Ratcliffe 2005), public health (Rushton 2003), home-range analysis (Seaman and Powell 1996), astronomy (Alard 2000), and landscape genetics (Epperson *et al.* 2010). In ERW applications, KDE can be used to interpolate contamination values in areas where there are no observed features.

In commercial GIS platforms such as ArcGIS, the KDE function is only applicable to points and lines, not to polygons. Therefore, ERW areas that were extracted from IMSMA^{NG} in the form of polygons were replaced by polygon centroids. A smoothly tapered surface was then fitted over each ERW area, with the highest value located at the point or centroid location. The value diminishes with increasing distance from the point/centroid, following a kernel function (e.g., in ArcGIS, the Epanechnikov kernel described in Equation 1 is applied) that reaches zero at a distance called "bandwidth" (Figure 3). The selection of the bandwidth value and its influence on the rendering of the map is discussed below. Additionally, the points and centroids were weighted by their estimated or calculated area, which was stored in the MySQL database. The output was calculated by summing all kernel surfaces as follows:

$$kde = S\,[1 - (r/h)^2]^2 \qquad \text{where } r < h \qquad (1)$$

$$0 \qquad \text{where } r \geq h$$

w here *kde* is the estimated density, *r* is the distance from the original point, *h* is the bandwidth and *S* is a scaling function equal to $15/16h$ for one dimension and to $3/\pi h^2$ for two dimensions (Silverman 1986):

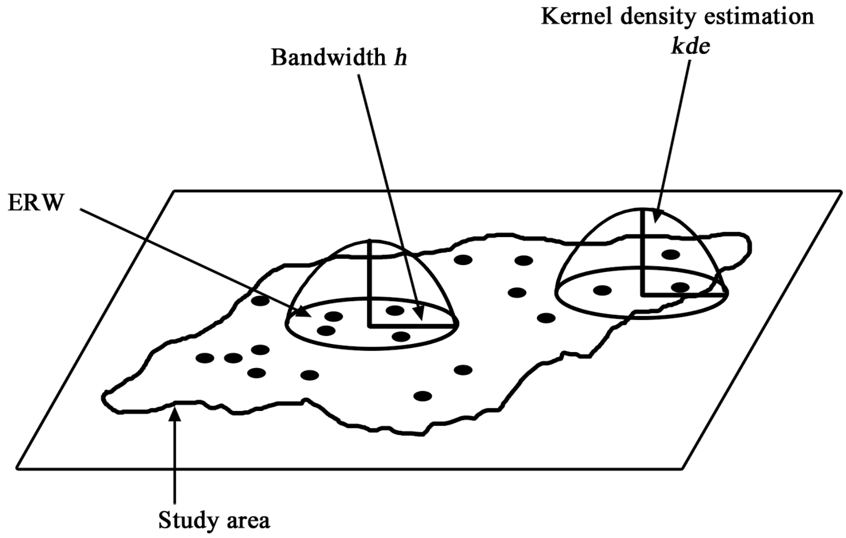


Figure 3: KDE of a multivariate point dataset

6.5 Method E: KDE applied to polygons

IMSMA^{NG} contains polygonal ERW data with variable shapes and areas. In particular, very long and narrow features (Figure 4) have been registered along country borders after conflicts and along mandatory crossing points such as roads.

Method D reduces these polygons to their respective centroids before conducting the KDE procedure. To obtain a closer representation of reality, we propose method E, which involves (1) filling polygons with random points using the algorithm provided by ArcGIS and (2) conducting a KDE on the points. In this method, the KDE is weighted by the area of the polygons, which is calculated from their geometry (coordinates of the vertices). Each random point is assigned a polygon area divided by the number of points in the polygon. The recording precision (i.e., the density of points scattered in the polygons) is called *RP*. Figure 4 shows the resulting KDE maps for methods D and E. In all KDE computations in our study, a cell size of 250 m was used for the KDE raster map. The cell size was chosen as a function of the target display scale, positional accuracy of the ERW data (accuracy at the meter to decameter scale was rare), requirements for obfuscation of the ERW location information, and practical requirements (Cf. Section 3.4).

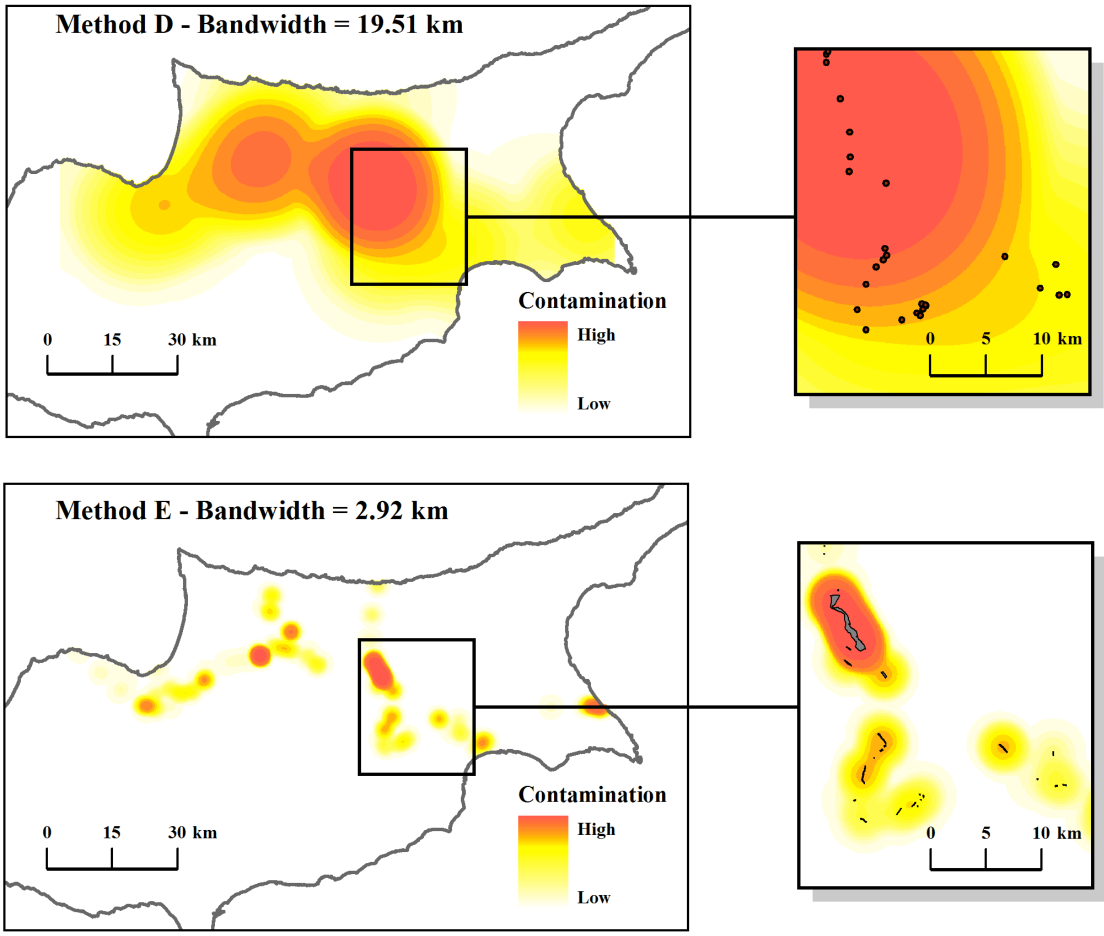


Figure 4: Comparison between methods D and E, both applied to the same dataset along the Cypriot buffer zone, where long polygons are encountered

Due to the high degree of heterogeneity in the spatial distribution of the input datasets, methods D and E were customized. Kernel bandwidth value adjustments and the effect of recording precision (*RP)* are described in detail in Section 7 and Section 8.1, respectively. The effect of the procedure for scattering points in the polygons is evaluated in Section 8.1.

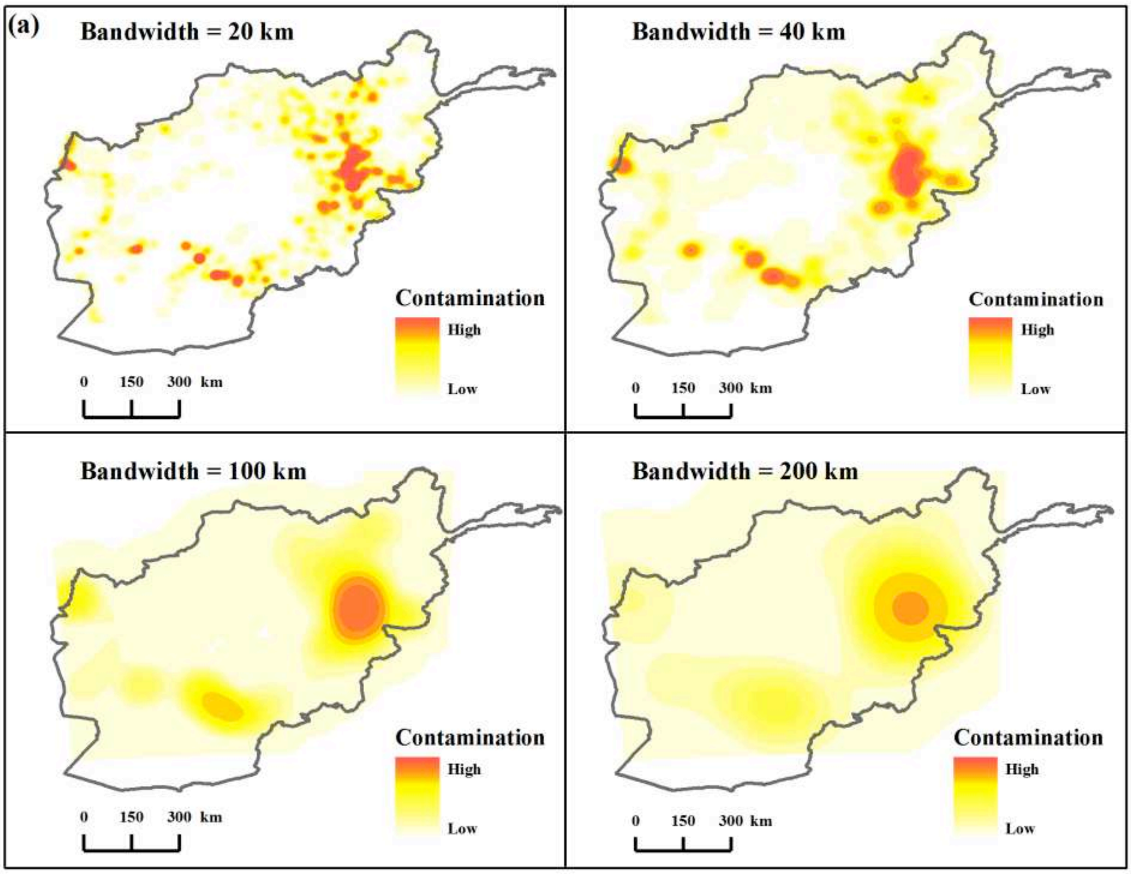
6.6 Method F: Cartograms

Cartograms are becoming increasingly popular among cartographers and scientists (Dorling 1993, Duczmal *et al.* 2011, Reveiu 2011, Sun and Li 2010 and others). In method F, the contamination values of the ERW areas are summed for each administrative unit. The geometry of the map is distorted to display the unit areas according to their contamination values. Heavily affected regions are expanded, while other regions are reduced. The cartogram algorithm by

Dougenik *et al.* (1985), which is also used in ArcGIS (“CartogramCreator”), generates contiguous-area cartograms and preserves administrative neighborhoods, allowing for the administrative units to be compared.

7 Customising KDE-based methods (D and E): adjusting KDE bandwidth

Described by De Smith *et al.* (2007, p. 178) as “often more of an art than a science,” bandwidth selection has a significant effect on the visualization and obfuscation of ERW (Herzog 2010). By choosing very small bandwidths, KDE maps tend to resemble to one-to-one dot maps, with small circles around ERW points. Not only are kernel peaks difficult to discern at small scales, but at large scales, the location of the ERW can be inferred to be the centre of the circular patterns of the kernel density map (Figure 5). Conversely, choosing a very large bandwidth could give the impression that small countries are contaminated across their entire geographical extents (e.g., Cyprus in Figure 4) and does not allow for discerning regional differences in contamination (Figure 5a). Moreover, a statistical analysis of the generated raster maps (Figure 5b) revealed that when a larger bandwidth was used, (1) the histogram of the map was more skewed, (2) the maximum density and the standard deviation were smaller, and (3) the kernel surface was smoother.


(a)
Bandwidth = 20 km
Contamination
High
Low
0 150 300 km
Bandwidth = 40 km
Contamination
High
Low
0 150 300 km
Bandwidth = 100 km
Contamination
High
Low
0 150 300 km
Bandwidth = 200 km
Contamination
High
Low
0 150 300 km

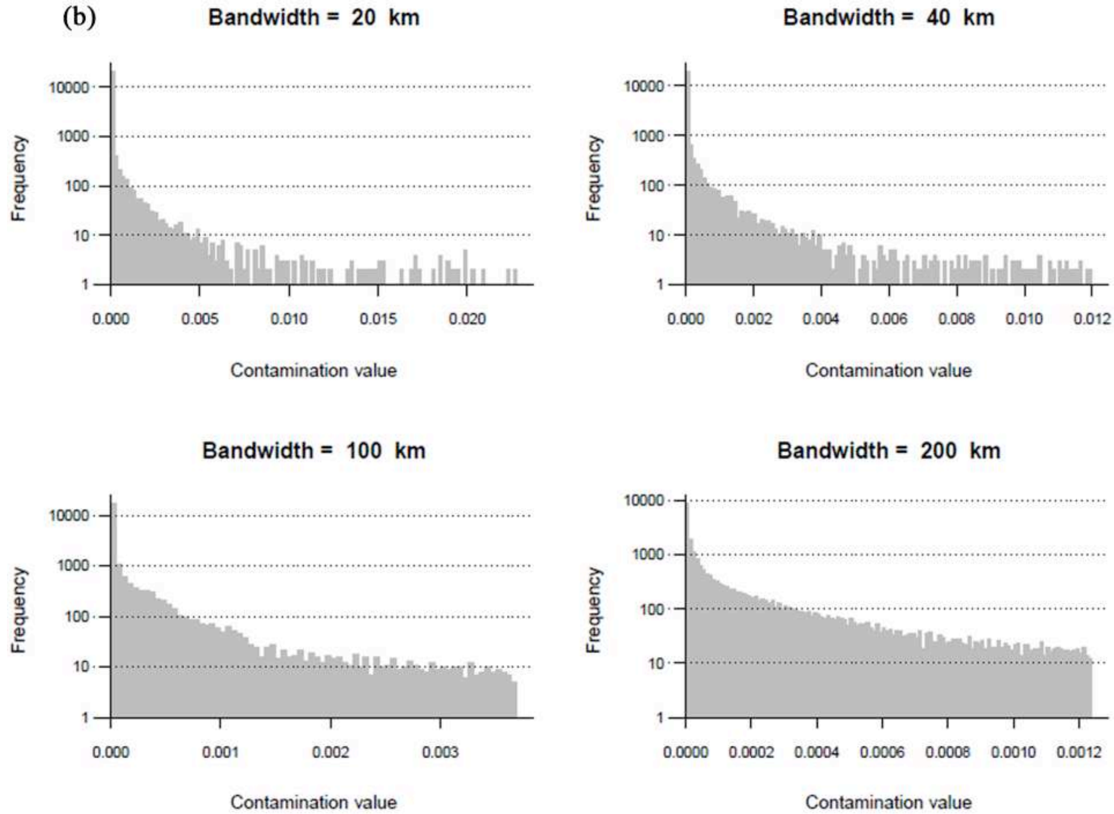


Figure 5: (a) Influence of kernel bandwidth on visualisation and obfuscation, (b) Logarithmic histograms of KDE in Afghanistan

What, then, is the correct process for determining the appropriate bandwidth? The default bandwidth provided by the ArcGIS Kernel Density tool, for example, is the height or width of the input hazards layer (whichever is shorter) divided by 30. The choice of 30 is arbitrary, has no statistical basis and does not consider the relative distribution of points across the area. Furthermore, the dimensions of the input hazard layers are strongly influenced by outliers.

Therefore, we attempted to estimate the correct bandwidth using an approach based on the input point datasets. Bailey and Gatrell (1995) proposed selecting a bandwidth value based on the number of points and the areal extent of the study area. In this method, however, no consideration is given to the spatial relationships between points. Other approaches and their applicability to one-dimensional samples have been described in the literature, most notably the Biased Cross-Validation and Unbiased Cross-Validation (Scott 1992), the Sheather-Jones Plug In (Sheather and Jones 1991, Jones *et al.* 1996, Loader 1999), and Silverman's Rule of Thumb (Härdle *et al.* 2004).

We made an attempt to adapt all of these methods for use with 2-D data. We obtained very large bandwidths in comparison with the country dimensions, up to 160 km in Tajikistan (Sheather-

Jones Plug In) and 130 km in Somalia (Unbiased Cross-Validation). This result motivated us to calculate bandwidth as the average distance to the *k*-th nearest neighbor (ADKNN). Inspired by Williamson *et al.* (1998), this method is designed to reflect the degree of clustering and the spacing of points, rather than the extent of the study area or the point dataset size. *k* is derived from Equation 2:

$$k = round\,[sqrt\,(n * P)] \qquad (2)$$

where *sqrt* is the square root of a number, *n* is the number of input ERW and *P* is a parameter provided to the user for adjusting the level of detail of the map.

8 Quantitative Evaluation of the Visualisation Methods

To o evaluate the fitness of the six cartographic visualization methods to the requirements stated in Section 3.4, a quantitative analysis was performed. The main findings of the analysis are presented in Section 8.1 and Section 8.2. The results provide an interesting new perspective on these methods and lay the foundation for the qualitative analysis discussed in 9.

8.1 Influence of the Sample Density with varying **P** *and* **RP**

Bandwidths were calculated using Equation 2 for each of the test countries and for values of *P* ranging from 0.1 to 50. The results obtained using method D are plotted in Figure 6a (comparison between countries) and in Figure 6b (comparison between random subsets of the same dataset). The results obtained with method E using the same dataset are plotted in Figure 6c, with points randomly scattered in polygons and a recording precision (*RP)* between 20 and 200 points/km^2. In this method, there is a risk that very small polygons will be omitted. To prevent this from occurring, each polygon is filled with at least one point. In Figure 6c, the largest sample contains 120’000 points.

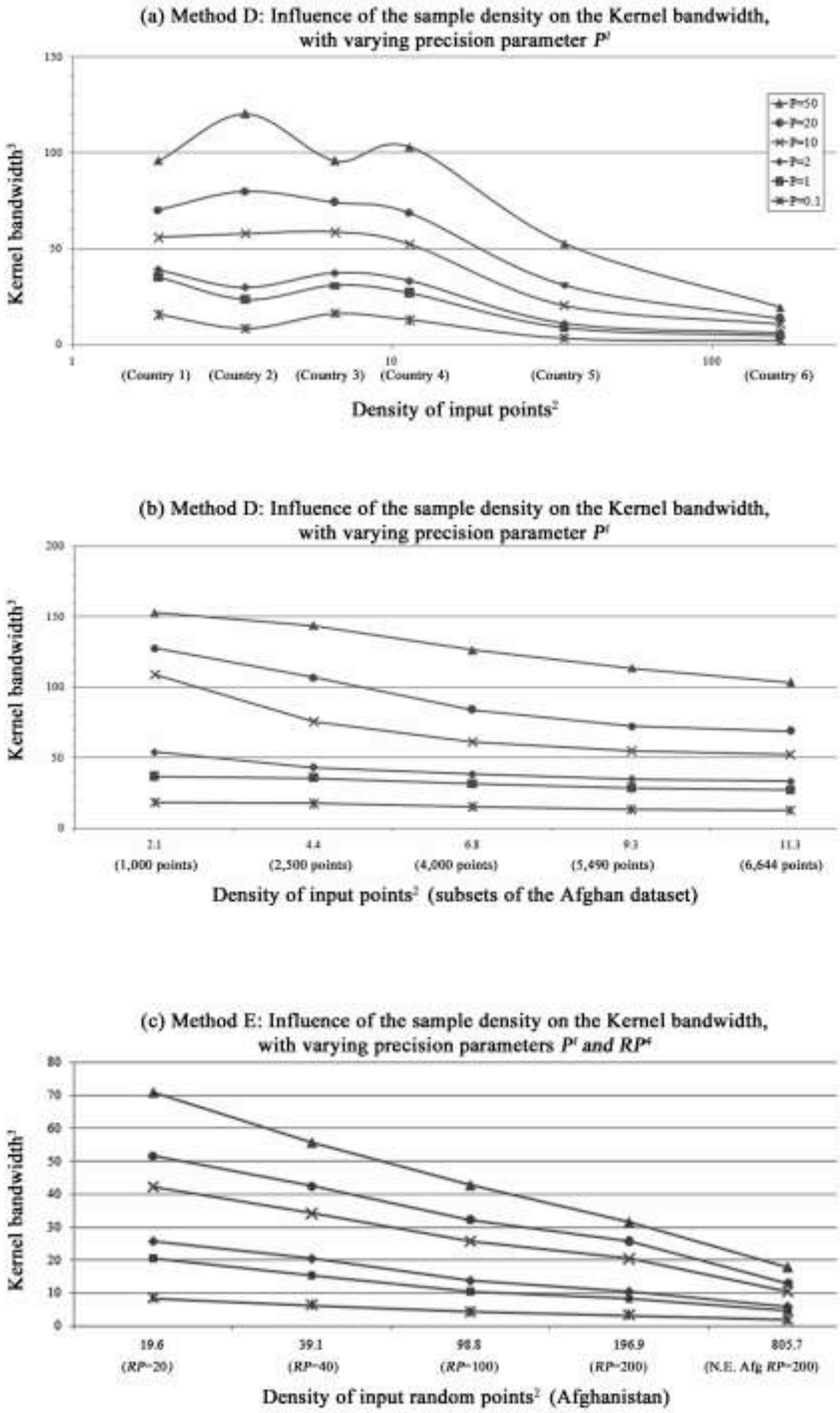


Figure 6: Effect of the density of ERW input data on the precision of the output maps, (a) For method D, using data from several test countries, (b) For method D using random subsets of the same dataset, and (c) For method E

[1]Precision parameter P is from Equation 2 and is used for adjusting the level of detail of the map

[2]Densities are expressed in 10^{-3} ERW/km^2

[3]Kernel bandwidths values are expressed in kilometres

[4]Recording precision (*RP*) is the density of points scattered in the polygons (number of points/km^2)

Figure 6 clearly demonstrates the effect of sample density on bandwidth. As sample density increased, (1) bandwidth values diminished and curbs stabilized, resulting in improved, smoother maps; and (2) the influence of parameters *P* and *RP* on the range of bandwidth values diminished. Nevertheless, users can still adjust the level of detail of the kernel density maps to a certain extent by varying parameters *P* and *RP*. This allows them to maintain control over the representation of contamination that they wish to show.

To evaluate the effect of the algorithm used for scattering points in polygons, we performed additional tests. (1) Some of the tests shown in Fig. 6c were repeated twice. Two tests with the same point density and the same *P* and *RP* values for the same set of polygons resulted in a difference in bandwidth values of less than 4%. (2) We also performed similar tests to the tests in Figure 6c, but this time the ERW polygons were filled with points that were regularly distributed in space. The difference in bandwidth values between the two tests with the same point density, *P*, and *RP* for the same set of polygons was less than to 3%. In addition, the difference in bandwidth diminished as input data density increased. Based on the results of these additional tests, the effect of the algorithm used to fill the polygons on the bandwidth is not significant. Additionally, as observed in Figure 6, the bandwidths computed with method D varied greatly among the different countries and consequently show very little adaptability. In contrast, the bandwidths computed with method E were smaller. Therefore, method E is a better fit for the data distributions, as shown in Figure 4.

8.2 Statistical Analysis of KDE-based Maps

A KDE was performed on the data from each test country, with bandwidths computed using the ADKNN method. The average, maximum, median, standard deviation and third quartile values are summarized in Table 2.

Table 2: Comparison between statistical indicators derived from KDE rasters, representing the six datasets. All values shown in the table are densities of ERW/km^2. They were computed on the test data and do not reflect the reality in the field

Test country	Sample size[1]	KDE bandwidth[2,3]	Mean	Max	Median	Standard deviation	Third quartile
Afghanistan	6’644	27.02	580	55’247	0	2’576	151
Cyprus	94	8.75	310	7’911	8	868	238
Iraq	196	35.08	1’34	76’060	0	5’862	31

			1				
Lebanon	1’496	4.68	1’508	98’585	0	5’012	8
South-Central Somalia	133	31.01	29	2’981	0	217	0
Tajikistan	202	23.47	116	2’609	0	305	23

[1]Number of points and polygon centroids

[2]Average distance (km) to *k*-th nearest neighbour, with *k* derived using Equation 2

[3]Precision parameter *P* equal to 1

For each country, the median value was systematically close to zero, and the third quartile value was much lower than the maximum value. This result demonstrates that kernel maps tend to highlight highly affected areas (in other words, they make the contamination problem more visible). Moreover, the third quartile values were relatively low. This result shows that KDE-based methods more effectively preserve areas with low contamination, especially compared to the methods used for maps B and C, which use aggregate data for a given administrative level.

The standard deviations were, on average, five times larger than the mean densities, and the number of non-zero values was much higher than in the original vector samples (in which the number of non-zero values was very close to zero). This result demonstrates that the use of KDE methods allows for the general distribution of ERW areas to be displayed without showing precise locations, which was consistent with the requirements of some users.

The figures in Table 2 show high variation from one country to another, especially in the “Mean” and “Max” columns, where the lowest value was fifty and thirty-seven times smaller, respectively, than the highest value. These results highlight the risk of exaggerating or understating the contamination problem. Developing a worldwide contamination map will require a number of checks in terms of representation, as we discuss below.

9 Discussion

In the following section, we discuss the strengths and weaknesses of the six cartographic visualization methods and compare them to the requirements given by each of the four target audiences mentioned in Section 3. The discussion is based on the quantitative analysis described in Section 8 and the requirements stated in Section 3.4. The outcomes of our meetings with experts (Section 3) were also important.

In particular, during the second focus group meeting, we showed the participants' paper contamination maps that were created using the cartographic visualization methods described above and the datasets from each country. The attendees were asked to respond individually to the questions listed below.

- Based on the paper maps, which cartographic visualization method(s) do you consider to be suitable for mapping ERW hazards?
- Which of these method(s) do you use the most?
- At which scale(s) does each method fit your cartographic needs? (global / national / sub-national / local)?
- Do you use other cartographic visualization methods for mapping ERW besides the methods used in the paper maps?
- What are the strengths and weaknesses of each of the six methods?
- Which method would best suit the needs of each of the four categories of users?

A group discussion was then held. The results of the discussion are summarized below. The discussion below is not structured according to the questions above, but it follows the main points raised by the focus group participants.

9.1 Ability to make the Contamination problem Visible

The ability to make the contamination problem visible is dependent on the scale of the representation. Methods B, C, D, E and F aggregate the original data at a scale at which the contamination problem is visible. In particular, cartograms have the capacity to enlarge small, heavily contaminated areas.

By making all cells an equal size (size = 250 m), the two KDE-based methods provide much more detail than the other methods, induce data fuzziness and ensure a smooth transition between areas of low and high contamination.

At smaller scales, method A maps become unreadable due to point symbol overlaps. Similarly, methods B and F become overloaded when the range of contamination values is too wide or when administrative units become too dense. Moreover, with a large number of administrative units, method F distorts administrative neighborhoods.

The issue of making the contamination problem visible is related to the question of data confidentiality. With the exception of method A, all of the methods preserve data confidentiality by aggregating the information. They also hide the amount and exact location of map items behind symbols (O'Sullivan and Unwin 2010). Kernel-based maps (D and E), conversely, do not preserve data confidentiality at large scales (Figure 5a).

Another issue is related to the question of country borders. Kernel maps of highly contaminated countries could show contaminated areas erroneously extending into neighboring countries, especially using method D with large bandwidths. Clipping the density raster layers to the boundaries of each country would not be a convenient solution to this problem, given the heterogeneity of distribution patterns across countries. Clipping the layers to the boundaries of each country would make the boundaries discernible and disrupt the continuous display of the data. Generating kernel maps country by country without sharing the information with other countries is one solution, and processing KDE maps using data compiled in national repositories is another alternative.

Finally, methods B and C make country boundaries visible, which might be politically problematic.

9.2 Capacity of Fitting the Original Data Distribution

Most data visualization methods inherently generalize and simplify the original data (Bertin 1977). Methods B, C and F assign one quantity to each administrative unit, and there is an inherent risk that changing the level of administrative unit would affect the message delivered by the map. This effect is known as the Modifiable Areal Unit Problem (MAUP), first described in detail by Openshaw (1984). The two KDE-based methods (D and E) are less sensitive to the MAUP because the units are identically sized grid cells with a resolution of 250 m. Furthermore, by using a much higher density of sample points than D, method E generates smaller bandwidths and is thus a better fit for the original vector data, especially when there are long polygons (Figure 4) located along country borders and roads, where having accurate information about ERW is crucial.

9.3 Simplicity of the Conveyed Message

In all of the maps (A, B, C, D, E and F), it is naturally understood that higher densities of symbols, larger symbols or darker colors all represent higher values (Gaspar-Escribano and Iturrioz 2011). According to O'Sullivan and Unwin (2010), proportional symbols induce an underestimation of larger values. Cartograms represent one degree of abstraction beyond choropleth maps (Dorling 1993). Cartograms may be difficult to use for GIS novices, who may consider the maps "funny-looking" (O'Sullivan and Unwin 2010, p. 79). Reading these maps also requires familiarity with the shape of the administrative units in the area being displayed.

9.4 Susceptibility to Data Uncertainty

With methods B, C, D and F, each point was weighted by its estimated or calculated area, which is stored as an attribute in $IMSMA^{NG}$. As mentioned earlier, area values and their reliability strongly depend on the hazard type (e.g., SHA or CHA). The accuracy of maps B, C, D and F is heavily dependent on this attribute, and the accuracy of maps using these methods would likely increase if the ERW were to evolve from SHA to CHA or to DHA status during the demining process. In contrast, method E uses the polygon surface area, which is more reliable because it was calculated from vertices' coordinates. Therefore, the reliability of method E is higher than that of methods B, C, D and F. This result suggests that the maps may be better in countries that have a high capacity for implementing demining operations.

9.5 Capacity of Combination with other Datasets

All of the proposed contamination maps are composed of a single layer. Each category of end users (Section 3.2) can combine the layers as needed with other datasets, such as administrative boundaries, socio-economic data, population density, topography, land cover, and logistics. For an example of an ERW map combined with a population density dataset, see Figure 7 (using method C) and Lacroix *et al.* (2011).

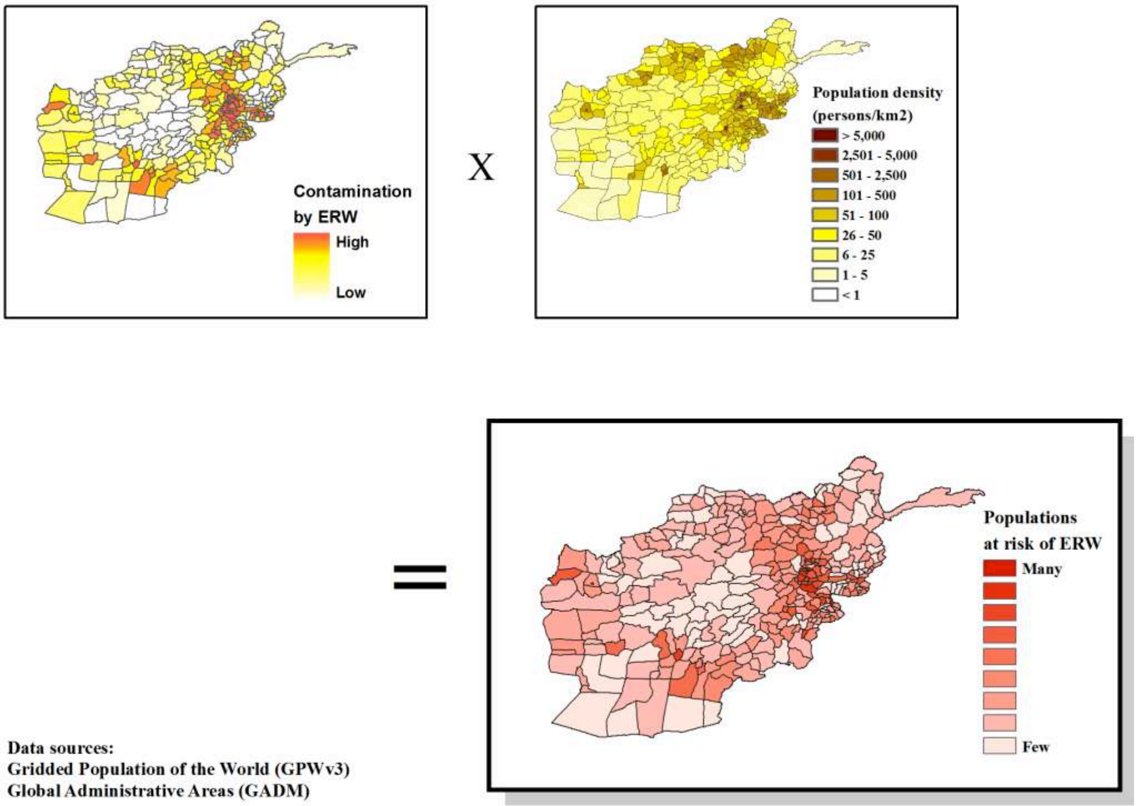


Figure 7: Possible application of the proposed cartographic visualization methods: multiplication of contamination maps (upper left: method C using Afghanistan data at the district level) by population datasets (upper right: Gridded Population of the World (CIESIN and CIAT 2005)) shows where people are most at risk (bottom)

Similarly, methods B, C, D and E use one visual variable (i.e., value, color, or size), which would make it possible to add a simplified base map (Bertin 1977) or overlay environmental data and would open the door to publication on a web platform.

9.6 Ease of use and Implementation

Methods A, B and C are easily depicted at any administrative level and easy to generate in any GIS package, even for users with limited "spatial ability and map experience" (Ozimec *et al.* 2010, p. 94).

Though KDE is included in most GIS packages, the algorithm that supports method D is not and was developed from scratch. Given the variation in bandwidth from one country to another (e.g., the discussion in Section 9.1), method D should be determined at the country level. IMSMA^{NG} is a useful tool for doing so because it already holds national databases that are comprised mostly of points. The precision parameter *P* of Equation 2 can be provided to the users as an input setting if they wish to generate density maps with a higher or lower level of detail.

Method E requires processing much more data than method D. Therefore, method E is more demanding in terms of computer performance, and it would be difficult to deploy method E to end users in the dozens of countries that use IMSMA^{NG}. Because method E shows a high adaptability to datasets, E is suitable for use at the global level to create a single worldwide map that compiles all national data. In practice, such a project will depend on the capacity of national mine action programs to provide IMSMA data as polygons.

9.7 Colour Scheme

As mentioned earlier, generating maps of ERW contamination at the global scale requires the development of a universal color ramp. To prevent the under-representation of regions of the world with low contamination and the over-representation of heavily affected areas, we decided to display the natural logarithm of the kernel density raster instead of the raw density values, following Newbury and Bright (1999). This method ensures that the contamination in all regions is measured on a similar scale and reduces the effect of the precision parameters *P* and *RP* on the output map (Figure 8). Changing the representation of the data can strongly influence the intended message and ultimately mislead the map reader (Ozimec *et al.* 2010), especially when applying data classification methods such as natural breaks (Jenks and Caspall 1971), equal intervals, quantiles and geometric intervals to very heterogeneous and skewed kernel distributions. These data classification methods are sensitive to the number of classes (Herzog 2010). They also disrupt the continuous nature of the density rasters and the smooth and fuzzy effect inherent to KDE maps. Therefore, data classification was not used. Instead, we developed a continuous color ramp based on the sample with the widest range of values. Following Müller *et al.* (2006), with the objective of attracting the reader's attention to heavily affected areas, the main colors of the color ramp are yellow, orange and red. To improve the readability of the maps and leave room for background layers (to publish the maps on a web server), transparency was applied to the hazard layer, and a second color ramp, ranging from white to yellow, was used for areas of low contamination (Figure 8). Finally, for reasons of confidentiality, no contamination figures were shown in the legend. Instead, the terms "low", "medium" and "high" were used.

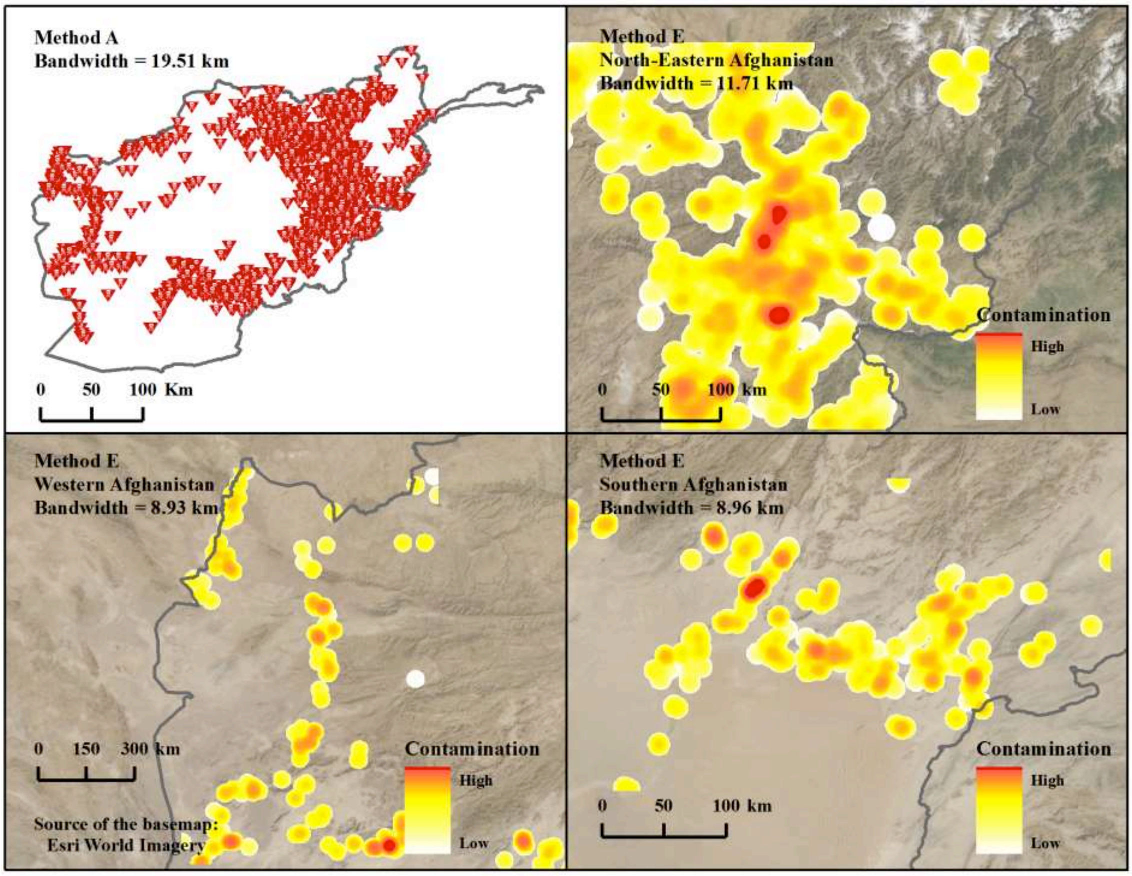


Figure 8: Maps showing contamination by ERW in Afghanistan. The map in the upper left corner corresponds to method A (dots). For the other maps, technique E (KDE on polygonal ERW) was applied in Afghan regions of varying extent and ERW density, and an identical colour ramp was used for each map

Figure 8 juxtaposes the least and most sophisticated of the six cartographic visualization methods and is a good way of highlighting the outcomes of this study.

9.8 Which Visualisation Methods for whom?

In this section, we draw conclusions about which of the proposed cartographic visualization methods are the most relevant for each category of actors, as a function of map scale.

Users outside the core field of mine action (i.e., donors and the general public) want to compare contamination levels between regions of the world without revealing the exact location of ERW. The message conveyed by the map must be intuitive and unambiguous. For this category of map consumers, method E emerged as the most suitable representation method in the form of a worldwide map combined with a universal color ramp, a basic ordinal legend and metadata in conformance with the OGC standards (OGC 2007a). Publishing this map on a web-GIS portal would help sensitize the users to the global mine contamination problem. Implementing this method requires that national mine action authorities supply polygon data.

At the national and sub-national scales, choropleth maps may also be helpful in providing supporting information for this category of users.

As mentioned earlier, *directors of national mine action programs* need maps at the national and regional levels. One purpose of these maps is to support strategic decision making about the use of resources. Another objective is for the directors to be able to present summaries of their achievements to other actors. Methods B, C, D, E and F are likely candidates at these scales (Sections 9.1 and 9.6). Method E has a long computation time and would therefore be difficult to use in 60 countries (Section 9.6). Method F might be difficult for GIS novices to use (Section 9.3). Methods B and F become overloaded with wide ranges of contamination values or dense administrative units (Section 9.1). Method C is already in use in some programs, but method D can be used to show more details (Section 9.1), is less sensitive to the MAUP (Section 9.2), preserves areas of low contamination (Section 9.2), stores data at the national level (Section 9.6), and is likely to encourage the sharing of information (Section 8.2). Method E handles polygons, which disqualifies it as an option for repositories in which ERW are mostly recorded as points. Based on these criteria, it was decided that method D would be automated and implemented as a standard in the IMSMA^{NG} cartographic module. This action should make it easier for directors to disseminate maps inside and outside of the mine action community at the national and regional levels.

Methods B, D and F are also likely candidates for helping *operations officers* make decisions at the regional and sub-regional levels. Methods B and F, however, are not recommended for the reasons described in the previous paragraph. Method A, combined with topographic and logistics layers (Section 9.5), is the most appropriate at the municipality level,

Database administrators and analysts work on the database, upstream of the maps, and aim to reduce uncertainty around data. Method A, combined with layers such as points of interest, is the most suitable at large scales (e.g., at municipality level and beyond)).

10 Conclusions and future Outlook

This study aimed to develop and assess a range of cartographic techniques that would allow for the visualization of contamination by explosive remnants of war (ERW) at different scales (ranging from the local (municipal) to the global scale) and for different groups of actors involved in mine action.

The novelty of this work can be observed from several perspectives. First, for actors in the mine action community, the study defined the requirements of ERW mapping for various user groups working at different scales. Second, the study provides a comprehensive framework and set of tools to visualize ERW contamination data. The systematic comparison and evaluation of six different cartographic visualization methods allowed for each method to be evaluated in terms of its relevance for each of the four categories of mine action stakeholders and at different scales. At the global scale, for example, potential donors can be made aware of the problem of worldwide contamination by ERW and of the regional variation and hot spots of ERW contamination using method E. Third, the paper represents innovation within the scientific community. An extension of the traditional kernel bandwidth selection technique is proposed for KDE-based visualization methods. This technique provides close-to-reality representation of points and polygons at large scales (i.e., sub-national, national, global) for any spatial data distribution, provided that a universal color ramp is used (such a color ramp was proposed, but it may be further improved). Finally, we made these cartographic visualization methods available to the humanitarian demining community.

The work presented here also shows potential for further contributions beyond this study. The implementation of the two KDE-based method E could be a first step towards the sharing of geospatial ERW data as a continuously maintained resource that is freely accessible to both the public and private sectors (Ryttersgaard 2001). The data could be shared across institutional, regional, and national borders using compatible technology (Granell *et al.* 2009), while preserving data non-disclosure agreements and allowing users to control the level of detail they want to share. For several reasons highlighted in this study, our work should encourage national programs to share a maximum amount of their data in future (Barlow 2003), not only for the mine action community but also to promote interdisciplinary scientific work (Köhler *et al.* 2006). Combining ERW contamination maps with other layers (e.g., population density, strategic infrastructure, points of interest, and development areas) could help decision-makers determine the socio-economic impacts of hazards and prioritize future surveys (Benini *et al.* 2003, Alegría *et al.* 2011).

Because the reliability of the kernel maps varies with the density of the input data, map consumers should be made aware of the risk of exaggeration or underrepresentation of ERW contamination. In addition, by pointing out the degree of uncertainty in point data and the potential reliability issues of each cartographic visualization method, we as cartographers assume our responsibility to inform end users about the maps' limitations (Evans 1997).

The main lessons learned during this study are the following. First, map users in the mine action community are more interested in the visual results of the maps than the methods and algorithms with which the maps were developed. Second, users need easy-to-use tools, and the users should be spared the complexity of the algorithms used. Third, our research began three years ago, and it appears that it will take some time before dozens of countries establish the use of methods such as D and E. The successful implementation of these methods will depend on our ability to efficiently demonstrate the benefits of the methods and modify them based on user feedback.

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